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Effects of a Micrometeorite Stream on the Accuracy of Astrometric Measurements by Scanning Space-Borne Instruments

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Abstract—The effect of micrometeorite impacts upon the surface of a spacecraft on the accuracy of astrometric measurements made by scanning with instruments onboard the spacecraft is considered. This effect is shown to be marginal for HIPPARCOS measurements. However, disregarding this kind of effect for all the currently projected spacecraft may result in the declared measurement accuracy being unachievable. Spacecraft maintaining constant spatial orientation during measurements are essentially not subject to the errors caused by collisions with micrometeorites. © *2000 MAIK "Nauka/Interperiodica".*

Key words: *astronomical observing techniques, instruments; Solar system—planets, comets, asteroids, heliosphere*

INTRODUCTION

The late 1980s to the early 1990s saw a remarkable event—successful realization of the HIPPARCOS project (Perryman *et al.,* 1989)—which proved great advantage of using space-borne astrometric instruments and, in essence, determined today's prospects for developing astrometry. The HIPPARCOS satellite was launched in 1989 and completed its mission in 1992, having measured positions of about 120 000 stars with an accuracy of 0.7 arc milliseconds. The main result of this mission is the HIPPARCOS and TYCHO catalogs (Perryman *et al.*, 1997), which are now intensively used in different areas of astronomy, astrophysics, geodynamics, etc. However, the HIPPARCOS project did not permit the determination of proper stellar motions with accuracy sufficient for maintaining the coordinate system over long time intervals. To maintain the achieved precision of the HIPPARCOS catalog, additional observations of astronomical objects are thus required because of changing their positions in the course of time. This issue can be partially solved by means of observations with ground-based interferometers and traditional meridian circles equipped by the matrix detectors operating in the automatic mode.

The success of the HIPPARCOS mission stimulated the statement of new tasks with the proviso that a higher level of measurement accuracy is attained. After the completion of the HIPPARCOS project, space agencies in various countries put forward a series of astrometric space-borne projects, which provide the next step in developing our knowledge of the Universe. Some of these projects promise to improve the accuracy of determining positions and proper motions of stars by one or two orders of magnitude. The projects call for the measurement of both the limited number of stars (several thousands) and determination of positions and proper motions of many millions of cosmic objects. Along with astrometric determination of stellar positions, high-precision multicolor photometry is planned in these projects. A large variety of projects are based on interferometric principles, which allow for the measurement of angles with an accuracy of several arc microseconds, which is much higher than the instrumental diffraction limit. Such an accuracy will exceed by 2–3 orders of magnitude that achieved in the HIPPARCOS project. It is such an accuracy that is most attractive nowadays for solving current scientific problems.

According to the principle of taking astrometric measurements, all space projects can be divided into two groups: those involving a survey of celestial sphere by the scanning method and observations of objects with an instrument maintaining a constant spacecraft orientation during exposition. By now the astrometric measurements have been carried out aboard two spacecraft: the HIPPARCOS satellite and Hubble space telescope. Observations made with HIPPARCOS are performed by the scanning technique, while the Hubble telescope is constantly oriented toward the measurable object. The accuracy of astrometric measurements achieved by both instruments is about the same although HIPPARCOS performed wide-angle astrometry and the Hubble telescope, narrow-angle astrometry.

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An improvement of accuracy of measurements of celestial objects' coordinates reveals additional sources of measurement errors. At low accuracy, their role is negligible, and they are not considered at all. Micrometeorite impacts on the spacecraft surface is one of such sources of measurement errors. This effect is of prime significance when the measurements are made by the method of scanning of the celestial sphere.

EFFECT OF MICROMETEOR IMPACTS ON MEASUREMENTS OF OBJECT'S COORDINATES BY THE SCANNING TECHNIQUE

Scanning the celestial sphere from the HIPPARCOS satellite was made on the sky areas spaced apart at the base angle $\alpha = 58°$. Both areas were observed in a single field of view. Scans of different portions of the celestial sphere are obtained by moving the spacecraft rotation axis. Observation of a star in the same field of view makes it possible to determine a current value of the period of spacecraft rotation about its axis, while observation of the given star in the other field enables one to refine the base angle value. Thus, a complete closure at the great circle occurs at the rotation period. It is supposed that the angular rotation velocity is constant on this time interval. Any alteration of the rotation velocity on the interval equal to the one period of rotation about the satellite axis leads to measurement errors.

Consider the following model of astrometric measurements by the scanning spacecraft. Let the satellite have the spin period T and the base angle α. Then the time T^* of satellite rotation through the base angle is

$$T^* = T\alpha/2\pi, \tag{1}$$

where α is in radians. We denote the satellite mass by M; its moment of inertia, by I; and spacecraft's characteristic radius, by R. In the simplest model, a satellite of spherical shape with uniform density distribution is considered. Then, $I = 0.4MR^2$.

Consider the micrometeorite of mass m, which flies at the speed v and hits the satellite surface. According to the momentum conservation law, the additional rotation rate of the satellite caused by micrometeorite impact is

$$\Delta\omega = \frac{5}{2}\frac{mrv}{MR^2}, \tag{2}$$

where r is the impact flyby distance for the micrometeorite that struck the satellite surface. Assuming that the micrometeorite stream is isotropic, the additional angular velocity directed along the spacecraft rotation, caused by the impact of a single micrometeorite, is obtained by integrating over all directions:

$$\langle\Delta\omega\rangle = \frac{5}{8}\frac{mv}{MR}. \tag{3}$$

The error in measuring the angle $\Delta\varphi$ caused by the jump-like alteration of the spacecraft angular velocity, defined by formula (3), is

$$\Delta\varphi = \langle\Delta\omega\rangle T^*. \tag{4}$$

The micrometeorite stream in the Earth's neighborhood is well studied in the mass range from 10^{-18} to 1 g (Grun *et al.*, 1985; Divine *et al.*, 1993). Using the results of these studies, we devised the function $\Phi(m^*)$ that describes the stream of micrometeorites with mass above m^*. Knowing the spacecraft surface area and time T^*, we can easily estimate the mass m^* of the micrometeorite that collides with the spacecraft for the time T^*.

The $\Delta\varphi$ value determined in this way characterizes the error in determination of the base angle obtained from measurements of a single star. The measurement processing procedure for the HIPPARCOS satellite was published in the catalog by Perryman *et al.* (1997). With allowance for this technique, we obtain a considerably lower error because the data are processed simultaneously for a large number of stars. Thus, for HIPPARCOS, we obtain the following estimate for the error caused by the satellite collisions with micrometeorites: $\Delta\varphi$ = 180 arc microseconds. Micrometeorites producing such errors have a mass of about 6×10^{-11} g and strike the satellite on average every 20 minutes. In the time interval between the instants of observation of two measured stars, the effect of micrometeorite impacts is, as a rule, negligible. However, owing to the sporadic character of the micrometeorite stream, impacts of rather large bodies are also possible. These impacts are able, even in such short time interval, to introduce a significant error in the measurement of the angle between stars. Using the obtained dependence of the impact rate on the micrometeorite mass, one can readily estimate the probability of such events: rough measurement errors may reach a few arc seconds once a year and may exceed the accuracy of a single measurement (10 arc milliseconds) once a day. These estimates agree well with those made by the authors of the HIPPARCOS catalog. Processing procedure, according to the above method, leads to the smoothing of errors of single measurements, while the base angle is determined from observations of a large number of stars. Therefore, according to our calculations, the root-mean-square error, estimated for the entire sample of stars $\Delta\varphi^*$, is 5 arc microseconds. Taking into account the accuracy of the HIPPARCOS catalog (Perryman *et al.*, 1997), equal to 0.7 arc milliseconds (700 arc microseconds), such an error is negligible and, therefore, in no ways affects the accuracy of the results obtained. Our error estimate is consistent well with the results obtained by the authors of the HIPPARCOS catalog (Perryman *et al.*, 1997).

DISCUSSION

The estimate obtained by us for HIPPARCOS shows that the transition to the microsecond measurement

Table

Project	Nominal measurement accuracy, arc microsec	Satellite radius, m	Rotation period, s	Base angle	$\Delta\varphi$, arc microsec	$\Delta\varphi^*$, arc microsec
DIVA (Germany) (Roeser, 1999)	150	0.8	7200	100	22350	50
GAIA(ESA) (Lindegren and Perryman, 1996)	5	1.5	7200	58	1600	8
FAME 99(USA) (Horner *et al.*, 1999)	50	1.15	2400	81.5	250	0.6
Struve (Russia) (Ershov *et al.*, 1995)	500	1.5	8640	70	3300	40
LIGHT (Japan) (Yoshizawa *et al*, 1997)	50	0.75	8640	90	6750	100
HIPPARCOS(ESA) (Perryman *et al.*, 1997)	700	0.8	7680	58	180	5

accuracy makes it necessary to take into account collisions with micrometeorites when developing new projects of astrometric scanning instruments.

By now, a variety of projects of astrometric satellites have been suggested in which the measurements are taken by the sky scanning method. We estimated the value of $\Delta\varphi$ for some of these projects. Since the methods of processing the measured quantities are not outlined in detail in most of suggested and currently discussed projects of space-borne astrometric instruments, we assumed that these methods are similar to that employed in the HIPPARCOS mission. On this basis, we estimated the errors of the output catalogs due to collisions with micrometeorite streams. The results of these estimates are listed in the table.

We see from this table that the error $\Delta\varphi$ is large in all suggested projects. This error is comparable to or exceeds the error of individual measurements, implying that collisions with micrometeorites represent one of the most essential sources of measurement errors. Nevertheless, the accuracy stated for these projects can be attained by joint processing of observations of many stars. However, even in this case the error $\Delta\Phi^*$ value due to micrometeorite impacts was found to be comparable to the stated accuracy of the catalogs obtained in the projects.

It is known that micrometeorite streams have seasonal and random, hundredfold and more considerable, variations (McDonnel *et al.*, 1997). As a result, in scanning various portions of the sky in various seasons, zones with anomalous error value may appear, which deteriorates the quality of astrometric catalogs. When designing the projects with submillisecond accuracy, one should take into account the very fact of the influence of the micrometeorite stream, which imposes restrictions on the choice of sizes, mass, and rotation velocity of scanning instruments. A detailed examination of the effect of micrometeorites on the spacecraft is also required in observations of various portions of the sky in different seasons.

It is noteworthy that the projects of instruments maintaining a constant orientation in space during the exposition time, such as Lomonosov (Nesterov *et al.*, 1992), SIM (Denner and Anvin, 1999), and Osiris (Boyarchuk *et al.*, 1999), have virtually no errors due to collisions with micrometeorites.

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